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**DØ and CDF**

## **Boson Pair Production and Triple Gauge Couplings**

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For the DØ and CDF Collaborations

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# Boson Pair Production and Triple Gauge Couplings

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The DØ and CDF Collaborations measure boson pair production including  $W\gamma$ ,  $WW$ ,  $WZ$ ,  $ZZ$  and  $Z\gamma$  production in  $p\bar{p}$  collisions at  $\sqrt{s} = 1800$  GeV. New results, from direct measurements, are described including  $W\gamma$ ,  $WW$ , and  $Z\gamma$  production cross sections and limits on non-Standard Model triple gauge boson couplings. The limits on anomalous  $WW\gamma$ ,  $WWZ$ ,  $Z\gamma\gamma$  and  $ZZ\gamma$  couplings are the most restrictive available. Prospects for Run II are discussed.

## 1. Introduction

The Standard Model (SM) of electroweak interactions makes precise predictions for the couplings between gauge bosons due to the non-abelian gauge symmetry of  $SU(2)_L \otimes U(1)_Y$ . These self-interactions are described by the triple gauge boson (trilinear)  $WW\gamma$ ,  $WWZ$ ,  $Z\gamma\gamma$ , and  $ZZ\gamma$  couplings and the quartic couplings. Vector boson pair production provides sensitive ground for *direct tests* of the trilinear couplings. The CDF and DØ Collaborations have studied  $W\gamma$ ,  $WW$ ,  $WZ$ , and  $Z\gamma$  events produced in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV during the 1992-1995 Tevatron run (Run I) [1]. This paper describes the results of those studies.

### 1.1. $WW\gamma$ and $WWZ$ Couplings

A formalism has been developed to describe the  $WW\gamma$  and  $WWZ$  interactions for models beyond the SM [2]. The effective Lorentz invariant Lagrangian, after imposing C, P, and CP symmetry, is:

$$\frac{i\mathcal{L}_{WWV}}{g_{WWV}} = g_1^V \left( W_{\mu\nu}^\dagger W^\mu V^\nu - W_\mu^\dagger V_\nu W^{\mu\nu} \right) + \kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu V^{\nu\lambda},$$

where  $V$  means  $\gamma$  or  $Z$ . The factor  $g_{WW\gamma}$  is  $e$ ;  $g_{WWZ}$  is  $e \cot \theta_W$ . The couplings  $g_1^V$ ,  $\kappa_V$ , and  $\lambda_V$  are to be determined by experiment. In the SM,  $g_1^\gamma = g_1^Z = \kappa_\gamma = \kappa_Z = 1$  and  $\lambda_\gamma = \lambda_Z = 0$ .

\*For the DØ and CDF Collaborations

Electromagnetic gauge invariance restricts  $g_1^\gamma$  to 1; however,  $g_1^Z$  could be different from the SM prediction. The coupling parameters are related to the magnetic dipole moments ( $\mu_W$ ) and electric quadrupole moments ( $Q_W^e$ ) of the  $W$  boson:  $\mu_W = \frac{e}{2M_W}(1 + \kappa + \lambda)$  and  $Q_W^e = -\frac{e}{M_W^2}(\kappa - \lambda)$ , where  $e$  and  $M_W$  are the charge and the mass of the  $W$  boson [3].

The effective Lagrangian leads to vector boson pair production cross sections which grow with  $\hat{s}$ , the square of the invariant mass of the diboson system, for non-SM values of the couplings. In order to avoid unitarity violation, the anomalous couplings are parameterized as form factors with a scale,  $\Lambda$  (*e.g.*  $\Delta\kappa/(1 + \hat{s}/\Lambda^2)^2$ ) [4]. The cross section is enhanced, particularly at high  $\hat{s}$ , because the delicate cancellation of some SM amplitudes is destroyed. The total cross section depends quadratically on the anomalous couplings. Furthermore, the transverse momentum of the bosons is larger.

### 1.2. $Z\gamma\gamma$ and $ZZ\gamma$ Couplings

The trilinear  $Z\gamma\gamma$  and  $ZZ\gamma$  couplings are all expected to be zero in the SM at tree level. Deviations from the SM are characterized [5] by momentum dependent form factors  $h_i^V$  ( $i = 1, 4$ ), where  $V$  means  $\gamma$  or  $Z$ .  $h_1^V$  and  $h_2^V$  are  $CP$  odd, while  $h_3^V$  and  $h_4^V$  are  $CP$  even. Anomalous  $Z\gamma\gamma$  and  $ZZ\gamma$  couplings enhance the cross section and harden the photon  $E_T$  spectrum.

## 2. $W\gamma$ Production

### 2.1. Results from CDF

The CDF Collaboration has previously published [6] the results of the Run Ia analysis. Here we report on the analysis of  $67 \text{ pb}^{-1}$  of the Run Ib data, last updated in July 1995 [7].  $W\gamma$  events are identified by the presence on an isolated muon with  $|\eta| < 0.6$  or electron with  $|\eta| < 1.1$  and  $E_T > 20 \text{ GeV}$ . Missing transverse energy  $\cancel{E}_T > 20 \text{ GeV}$  is required. A photon with  $E_T > 7 \text{ GeV}$  is required within  $|\eta| < 1.1$ . The angular separation  $\Delta R(\ell\gamma) = \sqrt{\Delta\phi^2 + \delta\eta^2}$  between the lepton and the photon is required to be greater than 0.7. The  $\Delta R$  selection criterion reduces the contribution from events where the photon has radiated from the lepton. CDF found 109  $W\gamma$  candidates. The background, mainly from  $W + \text{jet(s)}$  where a jet mimics a photon, is expected to be  $26.4 \pm 2.7$  events. Limits on anomalous  $WW\gamma$  couplings [8], from a fit to the photon  $E_T$  spectrum, are as follows. For  $\Lambda = 1.5 \text{ TeV}$ ,  $-1.8 < \Delta\kappa_\gamma < 2.0$  and  $-0.7 < \lambda_\gamma < 0.7$  at 95% CL.

SM  $W^\pm\gamma$  production has a radiation zero [9] at  $\cos\theta^* = \pm 1/3$ , where  $\theta^*$  is the angle between the incoming quark and photon in the  $W\gamma$  rest frame. Requiring  $\Delta R(\ell\gamma) > 1.5$  and that the invariant mass of the lepton and  $\cancel{E}_T$  is close to the  $W$  boson mass reduces the final state bremsstrahlung. A hint of a radiation zero is observed [7].

### 2.2. Results from DØ

The DØ Collaboration has previously published the results of the Run Ia ( $14 \text{ pb}^{-1}$ ) analysis [10]. Here we report on the Run I ( $93 \text{ pb}^{-1}$ ) combined analysis published recently [11].  $W\gamma$  events are identified by the presence of a high- $p_T$  lepton, either an isolated muon with  $|\eta| < 1.0$  or electron with  $|\eta| < 1.1$  or  $1.5 < |\eta| < 2.5$ .  $\cancel{E}_T$  indicative of the decay of a  $W$  boson is required. A photon with  $E_T > 10 \text{ GeV}$  is required within the same fiducial limits as the electron. As in the CDF analysis, requiring  $\Delta R(\ell\gamma) > 0.7$  reduces the number of events where the photon radiated from the lepton.

The combined data sample contains 127 events with a background, due mainly to  $W + \text{jet(s)}$  and  $Z\gamma$ , of  $43 \pm 5$  events. The cross section times

branching ratio,  $\sigma(p\bar{p} \rightarrow W\gamma + X) \times B(W \rightarrow \ell\nu)$ , with  $E_T^\gamma > 10 \text{ GeV}$  and  $\Delta R(\ell\gamma) > 0.7$  is  $11.3_{1.5}^{1.7}(\text{stat}) \pm 1.4(\text{sys}) \pm 0.6(\text{lum}) \text{ pb}$ , in agreement with the SM prediction  $12.5 \pm 1.0 \text{ pb}$ . Limits on anomalous  $WW\gamma$  couplings for  $\Lambda = 1.5 \text{ TeV}$  are  $-0.93 < \Delta\kappa_\gamma < 0.94$  and  $-0.31 < \lambda_\gamma < 0.29$  at 95% CL (the limits on  $CP$ -violating couplings  $\tilde{\kappa}$  and  $\tilde{\lambda}$  are similar). These are the tightest limits presently available for  $WW\gamma$  couplings.

One particularly interesting result is the exclusion, at 96% CL, of the  $U(1)_{EM}$ -only point  $\kappa = 0$   $\lambda = 0$ . Exclusion of this point is direct evidence that the photon couples to more than just the electric charge of the  $W$  boson. This is a triumphant confirmation of the SM gauge theory prediction.

## 3. $WW$ and $WZ$ Production

### 3.1. Results from DØ

The DØ Collaboration has studied the channels  $p\bar{p} \rightarrow WW \rightarrow \ell\bar{\nu}_\ell\ell'\nu_{\ell'}$  ( $\ell, \ell' = e, \mu$ ) and  $p\bar{p} \rightarrow WW(WZ) \rightarrow e\nu \text{ jet jet} + X$ . The background from  $W + \text{jet(s)}$  makes it difficult to extract a SM signal for the latter. Results of a search for a  $WW \rightarrow$  dileptons signal in the Run Ia data, leading to limits on  $WW\gamma$  and  $WWZ$  anomalous couplings, has been previously published [12]. The results of a search for a non-SM signal in the Run Ia data of the  $WW(WZ) \rightarrow e\nu \text{ jet jet}$  decay mode have also been previously published [13]. All of the Run Ia analyses (including the  $W\gamma$ ,  $WW/WZ$ , and  $Z\gamma$  analyses) are described in detail in a previous publication [14]. The combined Run Ia  $W\gamma$  and  $WW/WZ$  analyses provide anomalous coupling limits (assuming the  $WWZ$  and  $WW\gamma$  couplings are equal) of  $-0.71 < \Delta\kappa < 0.89$  and  $-0.44 < \lambda < 0.44$  for  $\Lambda = 1500 \text{ GeV}$  [14]. These analyses have been extended into Run Ib data.

The signature of the dilepton decay of a  $WW$  is two high- $p_T$  charged leptons along with large  $\cancel{E}_T$ . The  $E_T$  and  $\cancel{E}_T$  cuts depend on the particular decay mode  $ee$ ,  $e\mu$ , or  $\mu\mu$ , because of the difference in the  $p_T$  resolution of the DØ electron and muon detectors. In order to reduce the background from  $Z$  boson decays, cuts are made on the azimuthal angle between the  $\cancel{E}_T$  and leptons. Fur-

ther rejection of  $Z \rightarrow ee$  is obtained by requiring that  $|M_{ee} - M_Z| > 15 \text{ GeV}/c^2$ . For the  $e\mu\nu\nu$  decay channel, it was required that  $\Delta R(\mu, e) > 0.5$  to reject  $W$  bosons with a tracked-matched photon due to bremsstrahlung radiation from the muon. The background due to  $t\bar{t}$  production was reduced by requiring  $|\vec{E}_T^{\text{had}}| \leq 40 \text{ GeV}$ . Four (2  $e\mu$ , 1  $ee$ , and 1  $\mu\mu$ ) candidates were found in the Run Ib data with an expected background of  $2.6 \pm 0.4$  events. The 95% CL upper limit for  $\sigma(WW + X)$  is 43 pb. Limits on anomalous couplings for  $\Lambda = 1 \text{ TeV}$  are  $|\Delta\kappa| < 1.2$  and  $|\lambda| < 1.0$  at 95% CL, assuming the  $WW\gamma$  and  $WWZ$  couplings are equal, from the upper limit on the cross section.  $D\phi$  expects to have substantially improved anomalous coupling limits from a 2-dimensional fit to the two lepton  $p_T$ 's in the near future.

$D\phi$  has extended the search for a non-SM signal of the semileptonic decay modes of  $WW$  and  $WZ$  to the Run Ib data. An electron with ( $E_T > 25 \text{ GeV}$ ) and  $\cancel{E}_T > 25 \text{ GeV}$  which combine to form a transverse mass,  $M_T(e\nu) > 40 \text{ GeV}/c^2$ , indicate the presence of a  $W$  boson decay. In addition, two jets (formed with a cone radius of 0.5 in  $\eta\phi$  space) with  $E_T > 20 \text{ GeV}$  are required; they must form an invariant mass  $M(\text{dijet})$  between 50 and 110  $\text{GeV}/c^2$ . This provides the  $W$  or  $Z$  decay to jets. It is required that  $|E_T(\text{jet jet}) - E_T(e\nu)| < 40 \text{ GeV}$ . Requiring that the two bosons have nearly the same  $E_T$  reduces the background from  $t\bar{t}$ . In a data sample comprising  $82.3 \text{ pb}^{-1}$ , 399 candidates are found. Of these, only  $17.5 \pm 3.0$  are expected to be  $WW$  or  $WZ$  events. The remainder are principally  $W$  + jets and QCD fake events.

Limits on anomalous  $WW\gamma$  and  $WWZ$  couplings are made by fitting the  $E_T(e\nu)$  spectrum from the data with that expected of the background plus signal as a function of anomalous couplings. Combining the Run Ia and Run Ib semileptonic decay analyses yields limits, for  $\Lambda = 2000 \text{ GeV}$ , of  $-0.33 < \lambda < 0.36$  and  $-0.43 < \Delta\kappa < 0.59$  under the assumption that  $\lambda_\gamma = \lambda_Z$  and  $\Delta\kappa_\gamma = \Delta\kappa_Z$ . Limits using a different assumption, that the  $WW\gamma$  have the SM values (so as to contribute minimally to the cross section), shows the exclusion at more than 95% CL of the

point  $\kappa_Z = 0 \lambda_Z = 0$ . Exclusion of this point is direct evidence that the  $W$  boson couples directly to the  $Z$  boson. This is an important confirmation of the electroweak gauge theory first noted in a CDF publication [16]. This result has been submitted for publication [15].

### 3.2. Results from CDF

CDF has studied the dilepton and semileptonic decay modes of  $WW$  and  $WZ$  production. The  $WW(WZ) \rightarrow \ell\nu \text{ jet jet}$  ( $\ell = e, \mu$ ) analysis from Run Ia is long since published [16].

CDF has recently published [17] a study of  $p\bar{p} \rightarrow WW \rightarrow \ell\bar{\nu}_\ell \ell'\nu_{\ell'}$  ( $\ell, \ell' = e, \mu$ ) based on the Run I data. Two isolated charged leptons with  $E_T > 20 \text{ GeV}$  and  $\cancel{E}_T > 25 \text{ GeV}$  are required. In order to reduce background from  $Z$  boson decays, events with  $ee$  or  $\mu\mu$  invariant mass in the range  $75 - 105 \text{ GeV}/c^2$  are rejected and, similar to the  $D\phi$  analysis, events with  $\Delta\phi(\cancel{E}_T, \ell)$  are rejected if  $\cancel{E}_T < 50 \text{ GeV}$ . Finally, events with any jet with  $E_T > 10 \text{ GeV}$  are rejected in order to reduce the background from  $t\bar{t}$  production. Five (3  $e\mu$ , 2  $ee$ , and 0  $\mu\mu$ ) candidates were found in a data sample with an integrated luminosity of  $108 \text{ pb}^{-1}$ . The background, mainly from Drell-Yan lepton pair production and events with fake leptons, is  $1.2 \pm 0.3$  events. From this, CDF has enough evidence to quote a cross section  $\sigma(WW) = 10.2^{+6.3}_{-5.1} \pm 1.6 \text{ pb}$ . This is the first measurement of  $WW$  production and it is consistent with the SM prediction [18] of  $9.5 \pm 1.0 \text{ pb}$ . Limits on anomalous couplings for  $\Lambda = 1 \text{ TeV}$  are  $-1.1 < \Delta\kappa < 1.3$  and  $-0.8 < \lambda < 0.9$  at 95% CL, assuming the  $WW\gamma$  and  $WWZ$  couplings are equal, from the upper limit on the cross section.

CDF is in the process of extending the search for a non-SM signal of the semileptonic decay modes of  $WW$  and  $WZ$  to the Run Ib data. A high- $p_T$  electron or muon ( $> 20 \text{ GeV}/c$ ) and  $\cancel{E}_T > 20 \text{ GeV}$  which combine to form a transverse mass,  $M_T(\ell\nu) > 40 \text{ GeV}/c^2$ , indicate the presence of a  $W$  boson decay. In addition, two jets (formed with a cone radius of 0.4) with  $E_T > 25 \text{ GeV}$  are required; they must form an invariant mass  $M(\text{dijet})$  between 60 and 110  $\text{GeV}/c^2$ . This provides the  $W$  or  $Z$  decay to jets. Unlike the  $D\phi$  analysis, CDF requires that the jet-pair has

an  $E_T > 200$  GeV. This eliminates the need for a background estimate but limits the sensitivity of the analysis by pinching the acceptance to a region between  $200 < p_T(W) < 350$  GeV/c. The upper bound comes from the merging of the two jets at high  $p_T(W)$ .

No candidate events are seen in a  $110 \text{ pb}^{-1}$  Run IA + Run Ib sample. Preliminary results for the anomalous coupling limits at  $\Lambda = 2000$  GeV are  $-0.49 < \Delta\kappa < 0.54$  and  $-0.35 < \lambda < 0.32$  at 95% CL, assuming the  $WW\gamma$  and  $WWZ$  couplings are equal. These results are comparable to those from the  $D\bar{D}$  analysis. The two analyses have the tightest available limits for  $\Delta\kappa$ . The limits on  $\lambda$  are close to those obtained from the  $D\bar{D} W\gamma$  analysis noted above.

## 4. $Z\gamma$ Production

### 4.1. Results from CDF

The CDF Collaboration has previously published the results of the Run Ia  $Z\gamma \rightarrow ee\gamma$  ( $\mu\mu\gamma$ ) analysis [19]. An analysis [7] based on a  $67 \text{ pb}^{-1}$  subsample of the Run Ib data is presented here.

$Z\gamma$  candidates are identified by the presence of two charged leptons with large  $E_T$  and a photon. The  $E_T$  threshold is decreased from 20 GeV to 10 GeV for the lower  $E_T$  electron. The muon thresholds remain at 20 GeV. The pseudorapidity range is increased from  $|\eta| < 1.1$  (0.6) to  $|\eta| < 4.2$  (1.2) for the lower  $E_T$  electron (muon). The photon has the same selection requirements, including  $\Delta R(\ell, \gamma)$ , as in the  $W\gamma$  analysis described above. 31 Candidates are found with 18 in the  $ee\gamma$  and 13 in the  $\mu\mu\gamma$  decay modes. The background is expected to be  $1.4 \pm 0.3$  events, dominated by  $Z + \text{jet(s)}$  where the jet mimics a photon. The predicted number of events, including background, from the SM is  $26.3 \pm 2.6$  events. This is in agreement with the observed number. The highest  $E_T$  photons are 39 and 64 GeV. An event in the remaining (unanalyzed) part of the Run Ib data has a  $Z\gamma$  candidate with a photon of  $E_T = 182$  GeV. A fit of the observed  $E_T^\gamma$  to that expected from the SM + background yields limits on anomalous  $ZZ\gamma$  couplings. They are:  $|h_{30}^Z(h_{10}^Z)| < 1.6$  and  $|h_{40}^Z(h_{20}^Z)| < 0.4$ . The  $Z\gamma\gamma$  limits are similar.

### 4.2. Results from $D\bar{D}$

The  $D\bar{D}$  collaboration previously published the results of the Run Ia ( $14 \text{ pb}^{-1}$  analysis of the  $Z\gamma \rightarrow ee\gamma$  ( $\mu\mu\gamma$ ) (charged lepton) decay modes [20]. The analysis of the Run Ib charged lepton decay mode was updated for this conference and presented for the first time including both the  $ee\gamma$  and  $\mu\mu\gamma$  channels. The analysis of the Run Ia data for the  $Z\gamma \rightarrow \nu\nu\gamma$  decay channel was recently published [14,21] and will also be summarized below.

In the Run Ib analysis,  $Z\gamma \rightarrow ee\gamma$  candidates are identified by the presence of two electrons with  $E_T > 25$  GeV and a photon with  $E_T > 10$  GeV. The electrons and photons are required to fall with the pseudorapidity range  $|\eta| < 1.0$  or  $1.5 < |\eta| < 2.5$ .  $Z\gamma \rightarrow \mu\mu\gamma$  events are identified using either of two selection criteria. For the “tight” selection, two isolated muons with  $|\eta| < 1$  and  $p_T^{\mu_1} > 15$  ( $p_T^{\mu_2} > 10$ ) GeV/c must be identified using the muon tracking detectors. For the “loose” selection, one muon with  $|\eta| < 1$  and  $p_T^{\mu_1} > 15$  GeV/c is identified using the muon tracking detectors; the second muon is identified by the coincidence of the isolated energy deposition left by the muon through the longitudinal layers of the calorimeter with the azimuthal direction of the  $\cancel{E}_T$  corrected only for the “tracked” muon. The photon must have  $E_T > 10$  GeV and be in the same fiducial region as those from the  $W\gamma$  analysis. In both the electron and muon analyses, the photons are isolated from the electrons by requiring  $\Delta R > 0.7$  to remove final state bremsstrahlung photons. 29 Candidates are identified, 14 in the  $ee\gamma$  and 15 in the  $\mu\mu\gamma$  channels. The total expected background is  $5.4 \pm 1.0$  events, primarily from  $Z + \text{jet(s)}$  with a jet that mimics a photon and (muon channel only)  $W + \gamma$  events with an second, fake muon. The number of candidates agrees with the SM prediction of  $29 \pm 3$  events. The photon spectrum, shown in Fig. 1, shows qualitative agreement with the SM prediction. Two events in the  $ee\gamma$  channel have  $E_T^\gamma \sim 75$  GeV, dielectron invariant mass  $M_{ee} \sim M_Z$ , and  $M_{ee\gamma} \sim 200 \text{ GeV}/c^2$ . The probability for the SM signal + background to have two or more events with  $E_T^\gamma > 60$  GeV is 16%, including the  $\mu\mu\gamma$  decay mode. Anomalous coupling limits, formed

with  $\Lambda = 500$  GeV, are  $|h_{30}^Z(h_{10}^Z)| < 1.36$  and  $|h_{40}^Z(h_{20}^Z)| < 0.26$  at 95% CL. The  $Z\gamma\gamma$  limits are similar.

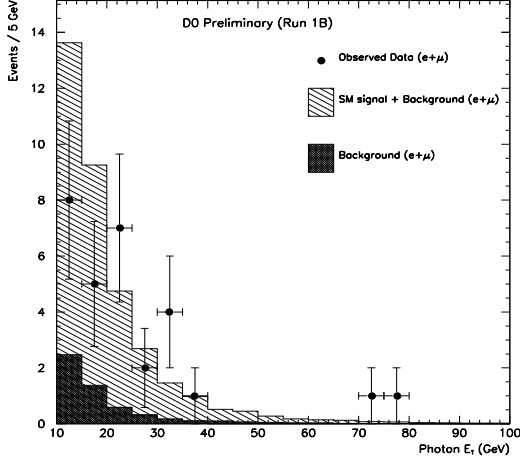


Figure 1. Photon  $E_T$  spectrum from the DØ  $Z\gamma \rightarrow ee\gamma$  ( $\mu\mu\gamma$ ) analysis of the Run Ib data.

The Run Ia  $Z\gamma \rightarrow \nu\nu\gamma$  analysis has the advantage of a 20% branching fraction compared to a 3.3% branching fraction for either of the charged lepton decay modes. In addition, there are no final state bremsstrahlung photons since the neutrinos have no electric charge. The excellent hermiticity and longitudinal segmentation of the DØ detector make it possible to identify events containing only a single photon with  $E_T > 40$  GeV balanced by  $\cancel{E}_T > 40$  GeV. Selecting events with no jets of  $E_T > 15$  GeV is important to reject background from  $W \rightarrow e\nu$  events with the electron misidentified as a photon. The longitudinal segmentation makes it possible to remove and estimate the size of the background from cosmic ray and beam related muon bremsstrahlung. The total expected background is  $5.8 \pm 1.0$  events. The predicted SM signal is  $1.8 \pm 0.3$  events. 4 Candidates are seen in the Run Ia data. The combined

Run Ia anomalous coupling limits for  $\Lambda = 500$  GeV are  $|h_{30}^Z(h_{10}^Z)| < 0.78$  and  $|h_{40}^Z(h_{20}^Z)| < 0.19$  at 95% CL. For  $\Lambda = 750$  GeV the limits are  $|h_{30}^Z(h_{10}^Z)| < 0.44$  and  $|h_{40}^Z(h_{20}^Z)| < 0.06$ . The  $Z\gamma\gamma$  limits are similar. These are the most restrictive  $ZZ\gamma$  and  $Z\gamma\gamma$  limits available.

## 5. Prospects

There will be substantial improvements in the anomalous coupling limits in the near future as CDF and DØ continue to analyze the Run Ib data. Ultimately, the two experiments will combine their results to produce Tevatron limits for Run I.

Presently DØ and CDF are working on their detector upgrades for Run II. The Main Injector will allow the Tevatron to provide  $2 \text{ fb}^{-1}$  data samples to each detector at  $\sqrt{s} = 2000$  GeV. For DØ, the addition of a solenoid magnet and new tracking system will improve the muon resolution. The CDF detector will have improved electron and photon acceptance in the forward direction.

Limits on anomalous couplings scale by approximately the 1/4 root of the luminosity for fixed  $\Lambda$  and assuming no improvement in technique. The large luminosity will provide upwards of 3000  $W\gamma \rightarrow \ell\nu\gamma$  events, 700  $Z\gamma \rightarrow ee\gamma + \mu\mu\gamma$  events, 100  $WW \rightarrow$  dileptons events, some 30  $WZ \rightarrow$  trileptons and a handful of  $ZZ \rightarrow e's$  and  $\mu's$  per experiment. CDF has already observed a  $ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$  event. This is the first Z boson pair candidate recorded. Qualitatively, the  $W\gamma$ , and perhaps, the  $WZ$  radiation zeroes will be unambiguously observed. Anomalous coupling limits will begin to probe the theoretical expectations.

## 6. Conclusions

In summary, the Tevatron continues to dominate observation of vector boson pair production. All of the pair production decay modes are accessible. Limits on anomalous coupling  $WW\gamma$ ,  $WWZ$ ,  $ZZ\gamma$ , and  $Z\gamma\gamma$  couplings remain, by a large margin, the tightest available. The prospects for Run II indicate the situation will

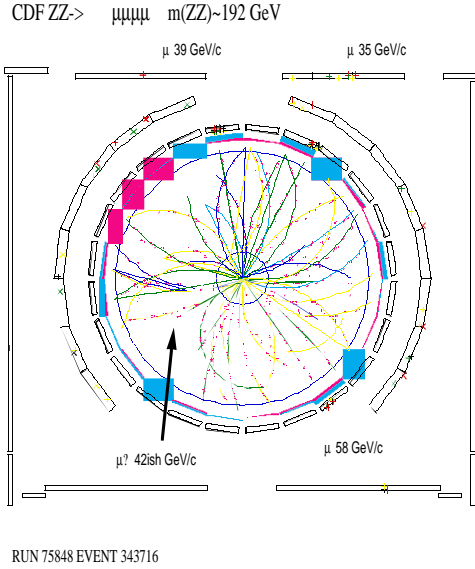


Figure 2. The  $ZZ \rightarrow \mu^+ \mu^- \mu^+ \mu^-$  candidate from the Run I CDF data.

remain so for some time.

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